NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2150

FLIGHT INVESTIGATION OF THE EFFECT OF TRANSIENT WING RESPONSE ON MEASURED ACCELERATIONS OF A MODERN TRANSPORT AIRPLANE IN ROUGH AIR

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Washington
August 1950

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SUMMARY

A flight investigation was undertaken on a transport airplane to determine the effect of transient wing response in rough air upon acceleration measurements at the center of gravity of the airplane. Flights were made in clear-air turbulence between altitudes of 3000 and 4000 feet for two speed conditions and different wing weights. Simultaneous acceleration measurements were taken at the center of gravity of the airplane and at several wing stations along the wing span from which the true airplane acceleration was determined.

A comparison of the results indicates that the peak recorded center-of-gravity acceleration increments were, on the average, over 20 percent higher than the true airplane acceleration increments. There appeared to be a small change in the acceleration discrepancy with the weight and speed change involved, but this effect could not be substantiated.

INTRODUCTION

In the flight operation of transport airplanes, atmospheric gusts constitute a principal source of loads. Knowledge of these loads is based primarily on V-G type of records and other acceleration measurements taken near the center of gravity of the airplane. A compilation and analysis of these and related stress measurements taken entirely on prewar airplanes is presented in reference 1. The interpretation of flight records has usually proceeded on the basis that the airplane acts as a rigid body and, for earlier types of airplanes, load estimation by this means was probably adequate. The different mass distributions, thinner wings, higher speeds, and various plan forms of more recent airplanes have caused increased concern with the dynamic effects of wing flexibility, and the use of peak center-of-gravity acceleration measurements in gust-load studies of these airplanes is open to question. Center of gravity as used herein refers to a fixed position in the fuselage.

Two principal effects of transient wing response on center-of-gravity acceleration measurements exist. One is a vibratory effect due to the excitation by the gusts of the natural modes of vibration of the airplane which causes the acceleration measured at the center of gravity to differ from the true airplane acceleration. The other is an aerodynamic effect due to the fact that the transient response causes a change in the total aerodynamic load that acts on the airplane. When vibratory response of the wing is important, therefore, center-of-gravity acceleration measurements may not be adequate for gust studies.

In order to obtain information on the effect of transient response on acceleration measurements and wing stresses, a flight investigation was undertaken on a modern transport airplane. Acceleration and stress measurements were made at a number of spanwise stations during flights through clear-air turbulence. The present paper deals with the acceleration phase of this investigation. Some consideration of the flexural characteristics of the test airplane led to the belief that the aerodynamic effect of structural vibration would be relatively small and, therefore, it is neglected. The primary purpose of this paper is, therefore, to investigate the vibratory effect on center-of-gravity acceleration measurements. Possible methods of evaluating or obtaining acceleration data free of vibratory effects are also considered.

The flight investigation was made in the vicinity of Baltimore, Md., in the spring of 1949 in cooperation with the Glenn L. Martin Co. The flights and instrumentation of the airplane were under the direction of the NACA and an NACA contract covered the flight time on the airplane. The U. S. Weather Bureau assisted in the selection of suitable flight days by furnishing daily turbulence forecasts.

APPARATUS AND TESTS

The characteristics of the test airplane are given in table I(a), the estimated spanwise weight and stiffness distribution in figure 1, and a three-view line drawing as figure 2.

The instrumentation consisted of an NACA recording accelerometer near the center of gravity and several electrical accelerometer units mounted at a number of stations along the wing span with the outputs recorded by means of a multichannel oscillograph. The location, type, and natural frequency of all accelerometer units used are given in figure 3. Lower-frequency units were used at the tip stations (station 554) to minimize high-frequency hash. The electrical accelerometer units were located as close as feasible to the elastic axis of the wing as determined from the manufacturer's ground vibration tests. The accelerometer units, at station 159 on both the left and right wing, were as close as possible to the nodal points, estimated from vibration tests, of the fundamental bending mode of the wing and were approximately equal in range to the NACA recording accelerometer at the center of gravity. A standard NACA airspeed-altitude recorder was used to obtain a record of airspeed and altitude, and an NACA $\frac{1}{2}$-second chronometric timer was used to correlate all records.

The tests consisted of flights through clear rough air over a course approximately 50 miles in length. The flight conditions of the three runs reported herein, designated as runs A, B, and C, are given in table I(b). The different weight conditions are due entirely to variation in wing fuel load. Runs A and B were made at 250 miles per hour for a weight change of 1,000 pounds per wing, which represents about two-thirds the fuel weight change experienced in normal operations. Runs A and C were consecutive runs at 250 and 150 miles per hour, respectively.

PRECISION

In the analysis of the flight records, both peak and faired readings were made. Consideration of the character of the records, repeatability of reading, and accuracy of the instrumentation leads to the belief that errors are less than ±0.05g for peak type of readings and less than ±0.10g when fairing is employed in the evaluation.

RESULTS AND DISCUSSION

The method of analysis consisted primarily in comparing the accelerations measured by an accelerometer near the center of gravity with the true airplane acceleration. For the purpose of this paper the acceleration at the nodal point of the fundamental bending mode is assumed to be the true airplane acceleration. Acceleration effects of the higher modes at this nodal point, where present, are taken into account by fairing. The nodal-point accelerations were used in order to eliminate the possible problem involved in discriminating between the effects of the fundamental mode and the gusts. In order to eliminate unsymmetrical influences, an average of the acceleration measurements taken at the nodal points of the left and right wing is used.

Examination of the flight records, of which sample portions are shown in figure 4, indicated that station 159 was, for practical purposes, the nodal point for all weight conditions of the tests, since, for portions of the records where the fundamental wing mode predominated in other traces, no evidence of the fundamental mode was present in the traces for station 159. In making these checks of the nodal-point position all the acceleration records were used, but only the nodal-point and center-of-gravity accelerations are considered further.

Examination of the acceleration traces for the nodal points (station 159) also revealed that, in addition to accelerations which were attributed to gusts and engine vibration, vibratory accelerations in the frequency range from 6 to 11 cycles per second were sometimes present. Vibration tests by both the manufacturer and the NACA indicated that, in most instances, the vibratory accelerations may be due to a coupling action between the wing and either the fin or stabilizer. Since these vibrations are considered irrelevant to the purpose of this paper, the acceleration traces were faired where these vibratory accelerations occurred. This fairing was essentially the mean of the envelopes of the vibratory accelerations.

Reproduced time histories of the nodal-point acceleration increments for the left and right wings, illustrative of portions of the records presenting evaluation difficulties, are shown in figure 5(a). Also shown, for purposes of comparison, is the fundamental wing period to the same time scale. In these histories, vibratory acceleration frequencies greater than 6 cycles per second are present for the negative acceleration increments and dissymmetry between right and left wing is present for the positive acceleration increment. The average of these curves, made after the vibratory accelerations were faired, is shown in figure 5(b), together with the corresponding time history for the center of gravity. Even though vibratory accelerations and dissymmetry were present, the history of the average nodal-point acceleration increment agrees with an approximate fairing of the center-of-gravity history in which all vibratory accelerations equal to and greater than the natural wing frequency are excluded. A further comparison of these measurements is given subsequently.

The maximum values of the average of the acceleration increments at the nodal points (higher modes faired) are shown as a function of the maximum or peak acceleration increments at the center of gravity in figures 6(a) and 6(b). These data are for a variation of wing weight and airspeed, respectively, and on each run a range of acceleration peaks was evaluated to represent the available data. Nodal-point acceleration values, from portions of the records in which vibratory accelerations above approximately 6 cycles per second were present, were faired in the evaluation and are denoted by a change in symbols in the figures.

The peak acceleration increments at the center of gravity, shown in figures 6(a) and 6(b), are equal to or greater than the nodal-point acceleration increments. Although appreciable scatter of individual points is evident, the trend of the data is roughly linear and indicates that the discrepancy increases with the magnitude of the acceleration increment. In table II least-squares solutions for straight lines fitted to the data $\left(\Delta n_{cg} = K_1 + K_2 \Delta n_{nodal}\right.$, where Δn is the acceleration increment$\left.\right)$ are shown for both the positive and negative acceleration data of runs A and B, there being insufficient range in the data of run C for this method to be applicable. Examination of the values in table II shows that the average values of the coefficients of the linear equation are $\pm 0.05g$ for the offset K_1 and 1.20 for the amplification factor K_2 and that these average values are within the probable error for the individual estimates. The dashed lines in figures 6(a) and 6(b) represent the equation with these average coefficients. In figures 6(a) and 6(b), the acceleration increments appear to be slightly less for the lower wing weight and lower speed of runs B and C than for run A, although no definite values could be substantiated. For the test airplane, it is evident that the peak recorded acceleration increment at the center of gravity in rough air is, on the average, the true airplane acceleration increment amplified by a factor of approximately 1.2 and further increased by approximately 0.05g.

In evaluation of time histories of acceleration near the center of gravity, fairing of the vibratory accelerations should yield the average nodal-point or airplane acceleration (see fig. 5), provided that the vibratory acceleration frequencies equal to and greater than the natural wing frequency are clearly defined and can be differentiated from gust accelerations. The results of this type of evaluation show good agreement (fig. 7) with the average nodal-point acceleration increments. It may also be noted that the results are substantially the same whether or not the nodal-point evaluation required fairing. This method of evaluation would be applicable to time-history center-of-gravity acceleration measurements with sufficient time resolution to discern the vibratory accelerations and provided that the vibratory and gust accelerations can be separated.

For the bulk of the data on the occurrence of acceleration values due to gusts, which are obtained by means of NACA V-G recorders (reference 1), fairing through the vibratory accelerations is generally not possible and indications corresponding to the peak acceleration data of figures 6(a) and 6(b) would be expected. In the range of acceleration measurements which are usually recorded by the NACA friction-damped V-G recorders, however, the inherent errors of the instrument approach in magnitude and may tend to compensate for the error of measurement caused by the vibratory effects of the wing, so that no valid correction can be applied. In the case of measurements made at the center of gravity with the new NACA oil-damped V-G recorders, the discrepancies as listed in table II would seem applicable for airplanes of the type tested.

Combining the electrical outputs of accelerometer pickups mounted at the nodal point of each wing has been suggested as a possible means of obtaining a more satisfactory measurement of airplane acceleration for gust studies. As a measure of the adequacy of such a procedure, since vibratory accelerations of higher modes may be evident at the nodal point of the fundamental mode and fairing may not be feasible, the records were evaluated to obtain peak measurements of this nature (fig. 8). It would appear from the data in figure 8 that the combined output of accelerometers at the nodal point (unfaired) would be a better measure of the airplane acceleration than peak or unfaired measurements at the center of gravity, although not so good as faired measurements at the center of gravity. This method would be applicable if there are no large shifts of nodal-point position with the changes in wing mass. The differences between the nodal-point acceleration and the combined unfaired outputs appear to be of the nature of an offset error in acceleration averaging approximately 0.05g for the test airplane.

CONCLUDING REMARKS

A flight investigation was undertaken on a transport airplane to determine the effect of transient wing response in rough air upon acceleration measurements at the center of gravity of the airplane. For the airplane tested the results show that in rough air the maximum or peak recorded acceleration increment at the center of gravity is, on the average, equal to the true airplane acceleration increment amplified by a factor of approximately 1.2 and further increased by approximately 0.05g. There appeared to be a small decrease in the acceleration discrepancy with the decrease in wing weight and speed of the tests, but this effect could not be substantiated.

The direct vibratory effects of wing flexibility can be corrected or compensated for in some cases through proper methods of evaluation or measurement. For the case of center-of-gravity acceleration measurements taken in rough air with the new NACA oil-damped V-G instruments, a reduction of the measured acceleration increments that can be ascribed to gusts by approximately 20 percent would seem to apply for airplanes of the type tested. For time-history measurements of acceleration near the center of gravity, evaluation of the acceleration values by fairing the fundamental and higher wing frequencies appears to yield an adequate measure of the acceleration of the airplane. Peak values obtained by combining the outputs of accelerometer pickups located at the nodal points of the wings yield a better measure of the airplane acceleration than peak center-of-gravity measurements, although not so good as faired center-of-gravity measurements.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Air Force Base, Va., May 10, 1950

REFERENCE

1. Rhode, Richard V., and Donely, Philip: Frequency of Occurrence of Atmospheric Gusts and of Related Loads on Airplane Structures. NACA ARR L4I21, 1944.

TABLE I

CHARACTERISTICS AND FLIGHT CONDITIONS OF TEST AIRPLANE

(a) Characteristics

Span, feet	93.3
Mean aerodynamic chord, feet	10.1
Wing area, square feet	870
Slope of lift curve, per radian	5.0
Aspect ratio	10
Center-of-gravity position, percent M.A.C.	22
Fundamental frequency, wing bending (ground vibration tests, W = 25,600 lb), cycles per second	3.8

(b) Flight conditions

Run	Average gross weight (lb)	Speed (mph)	Altitude (ft)
A	33,650	250	Between 3000 and 4000
B	31,550	250	Between 3000 and 4000
C	32,850	150	Between 3000 and 4000

NACA

TABLE II

LINEAR DESCRIPTION OF DATA BY LEAST-SQUARES SOLUTION

$$\left[\Delta n_{cg} = K_1 + K_2 \, \Delta n_{nodal}\right]$$

Run	Offset and probable error K_1	Amplification factor and probable error K_2
Positive acceleration increments		
A	0.08 ± 0.03	1.24 ± 0.06
B	0.06 ± 0.02	1.21 ± 0.06
Negative acceleration increments		
A	-0.05 ± 0.02	1.15 ± 0.05
B	-0.03 ± 0.02	1.20 ± 0.06

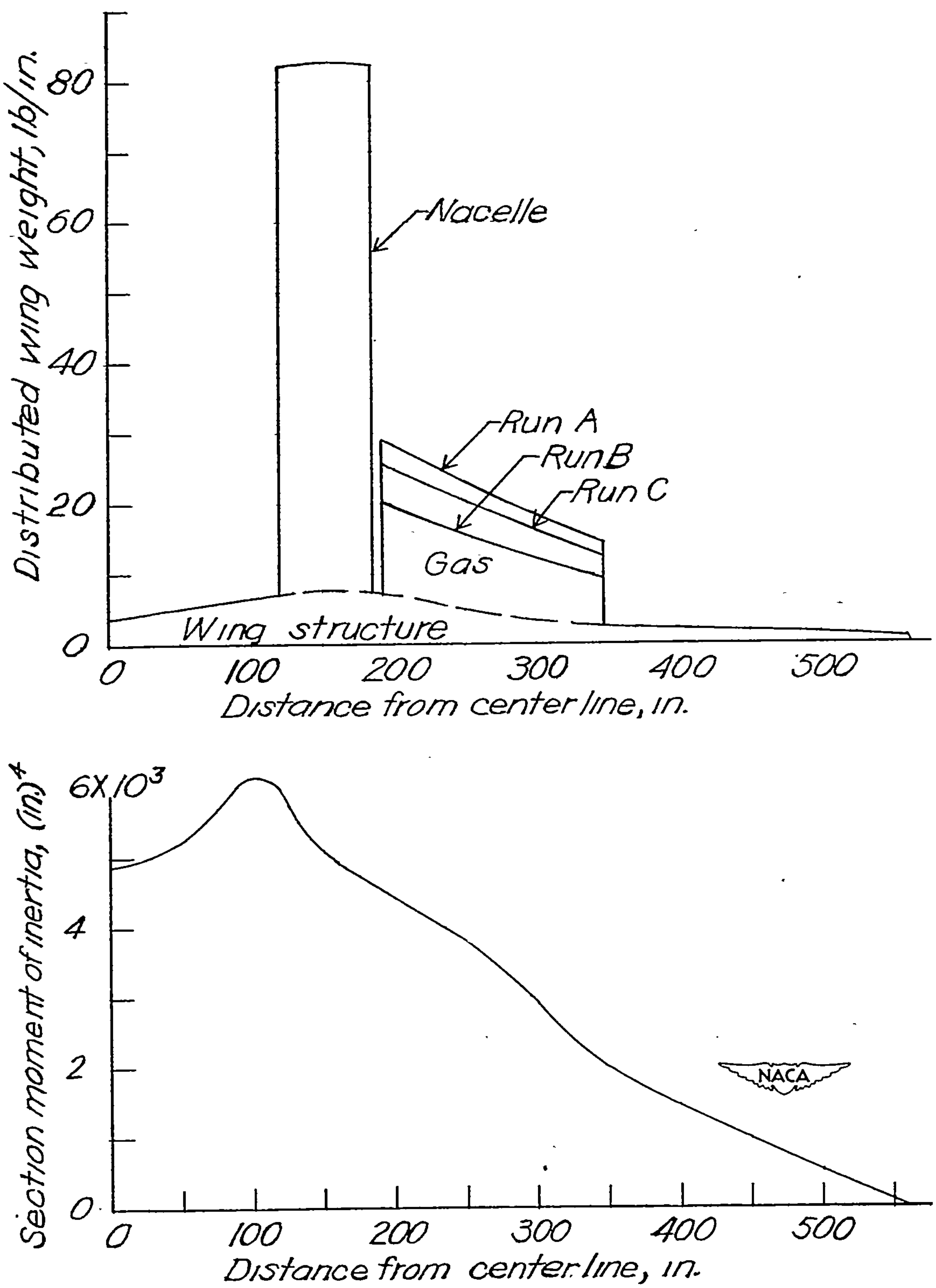


Figure 1.- Estimated wing weight and stiffness distribution.

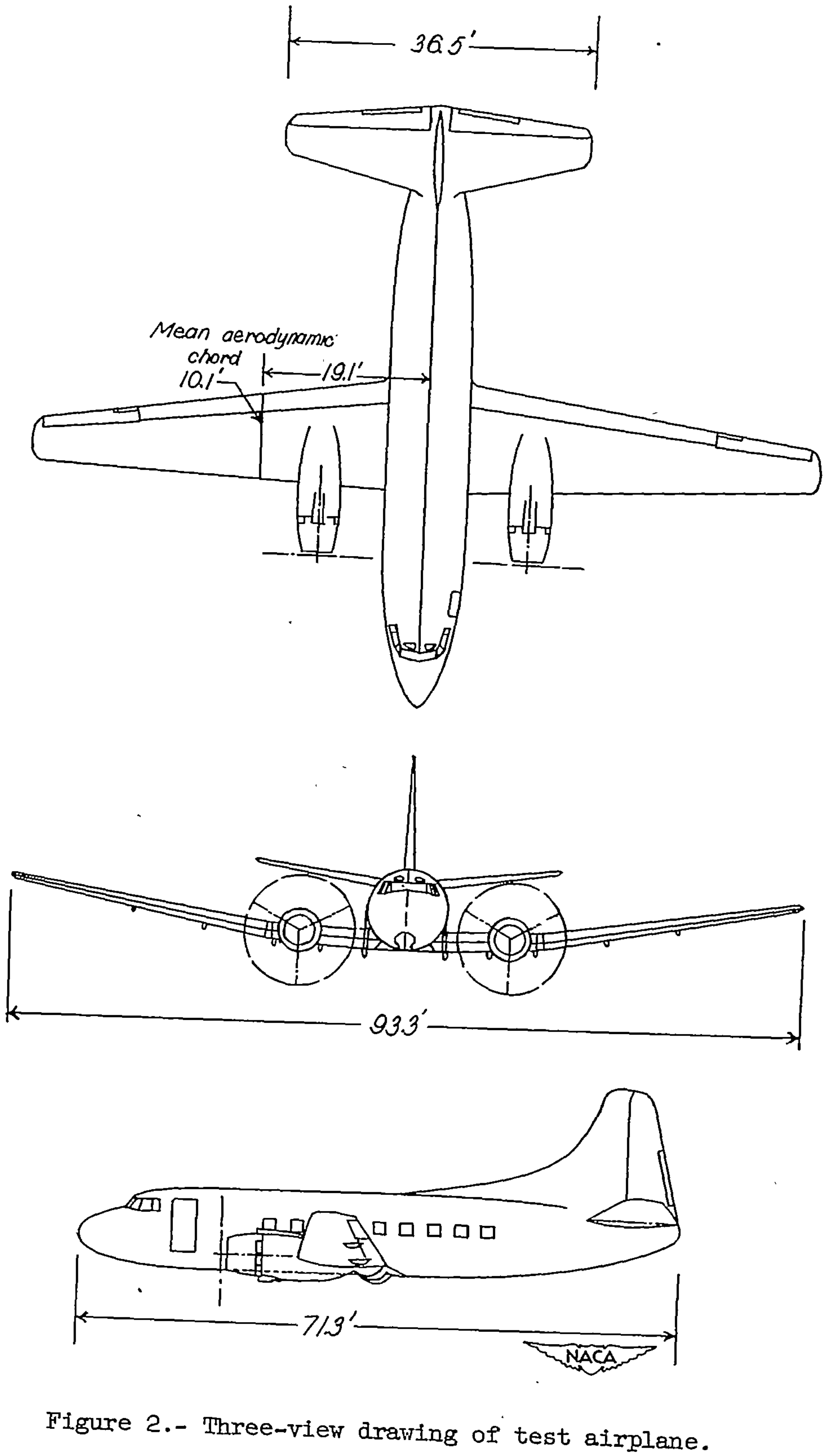
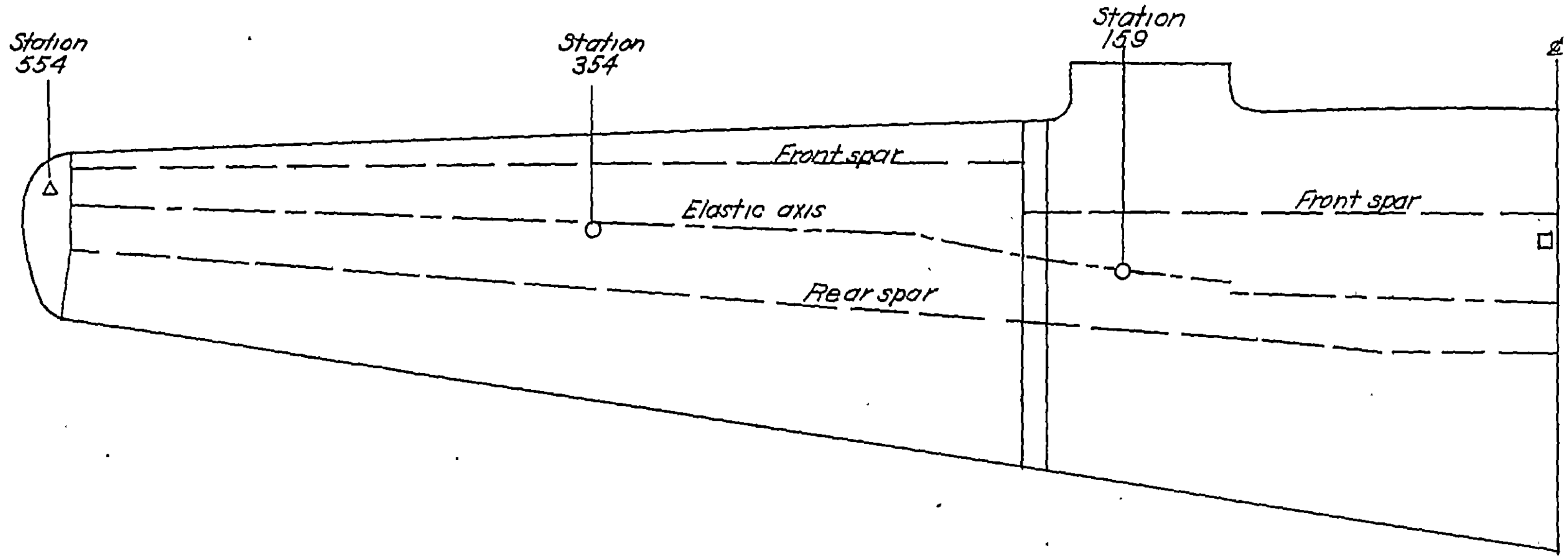


Figure 2.- Three-view drawing of test airplane.



	Type of accelerometer	Natural frequency, cps
○	Statham, electrical	55.0
□	NACA, optical	16.5
△	NACA, electrical	15.0

Figure 3.- Accelerometer locations in left wing of test airplane. (Installations at station 159 and station 554 were repeated in right wing.)

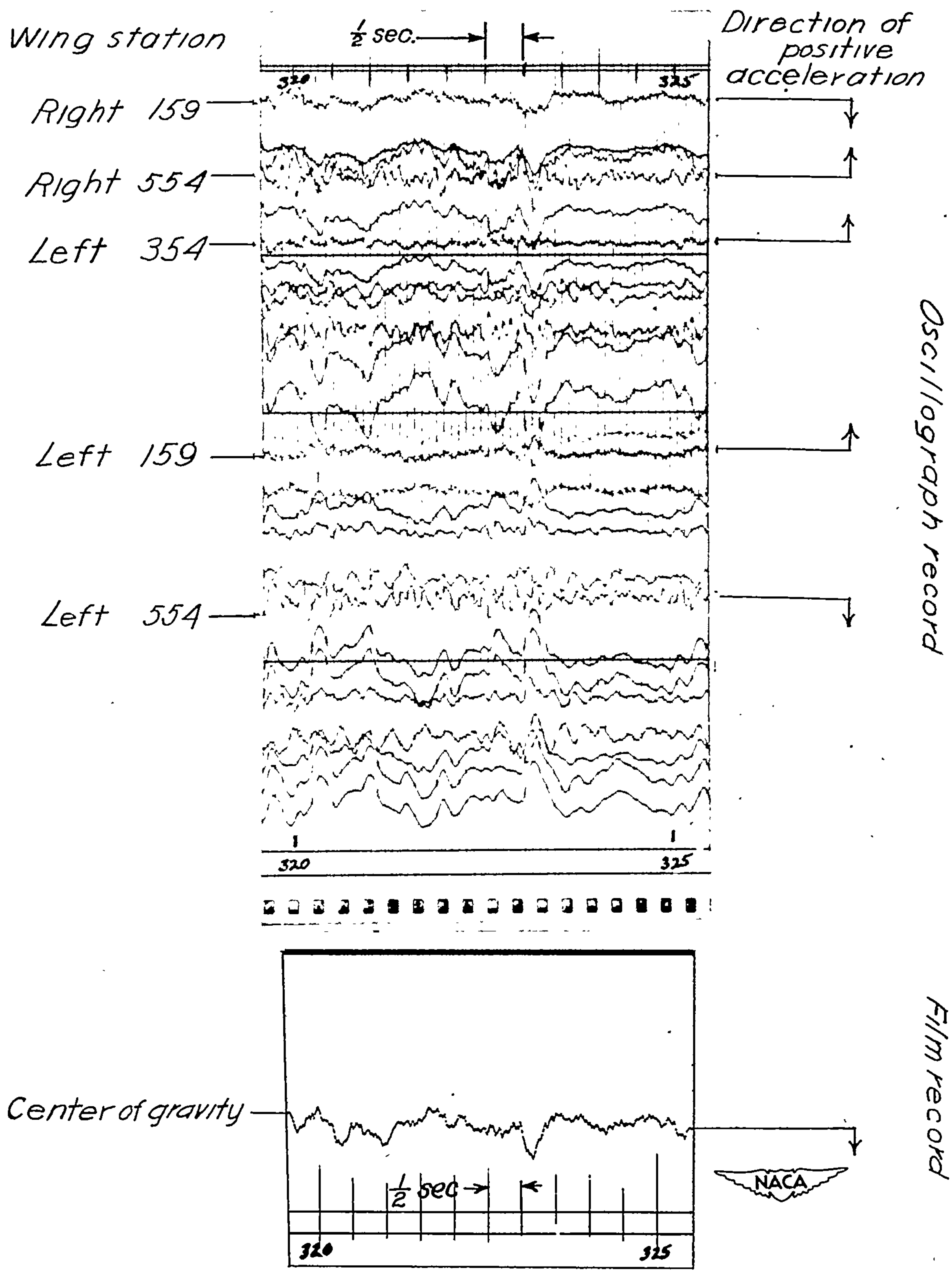
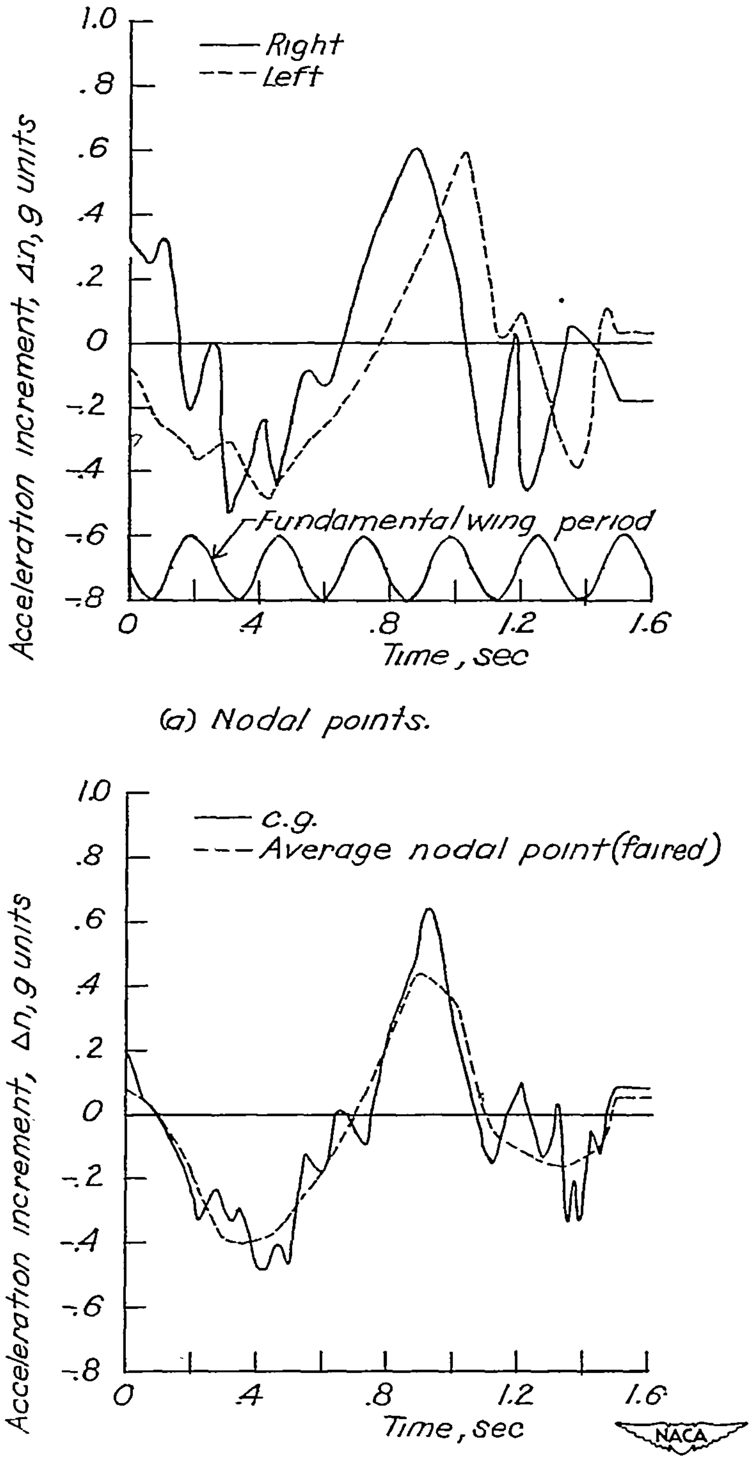
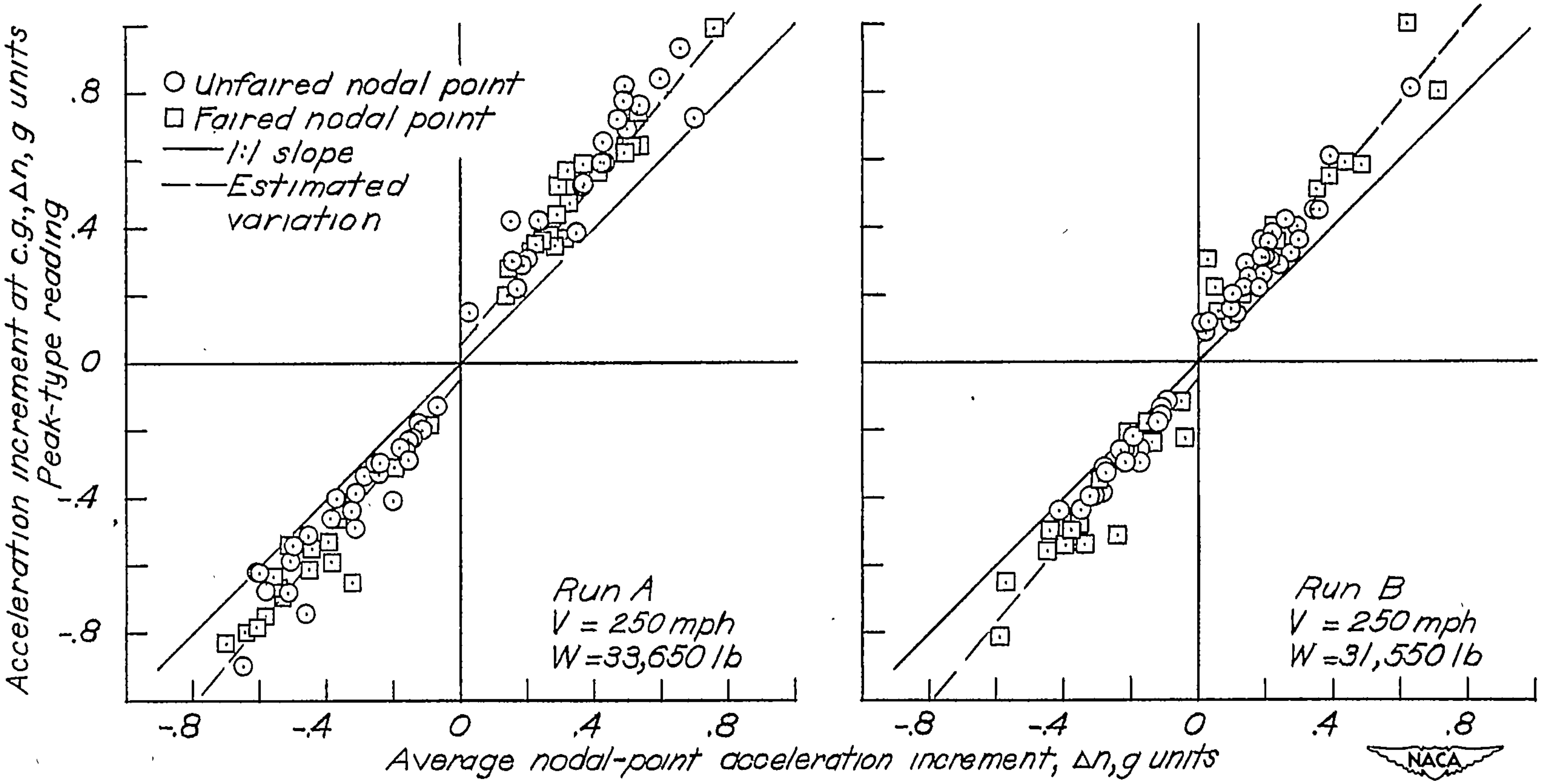


Figure 4.- Samples of records (only pertinent traces identified).



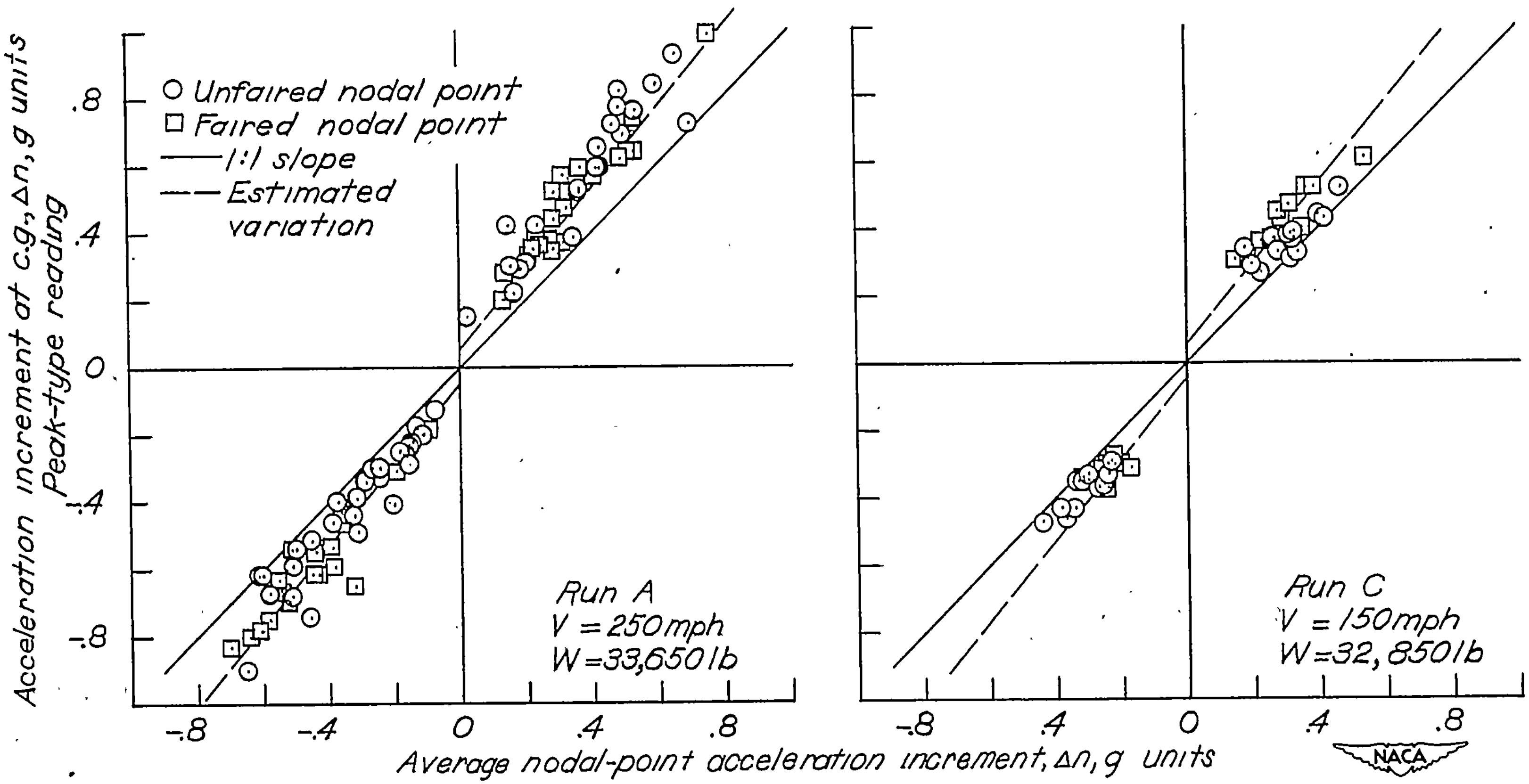
(b) Center of gravity against average nodal point.

Figure 5.- Time histories of acceleration in gust.



(a) Weight effect.

Figure 6.- Acceleration at center of gravity as a function of average nodal-point acceleration.



(b) Speed effect.

Figure 6.- Concluded.

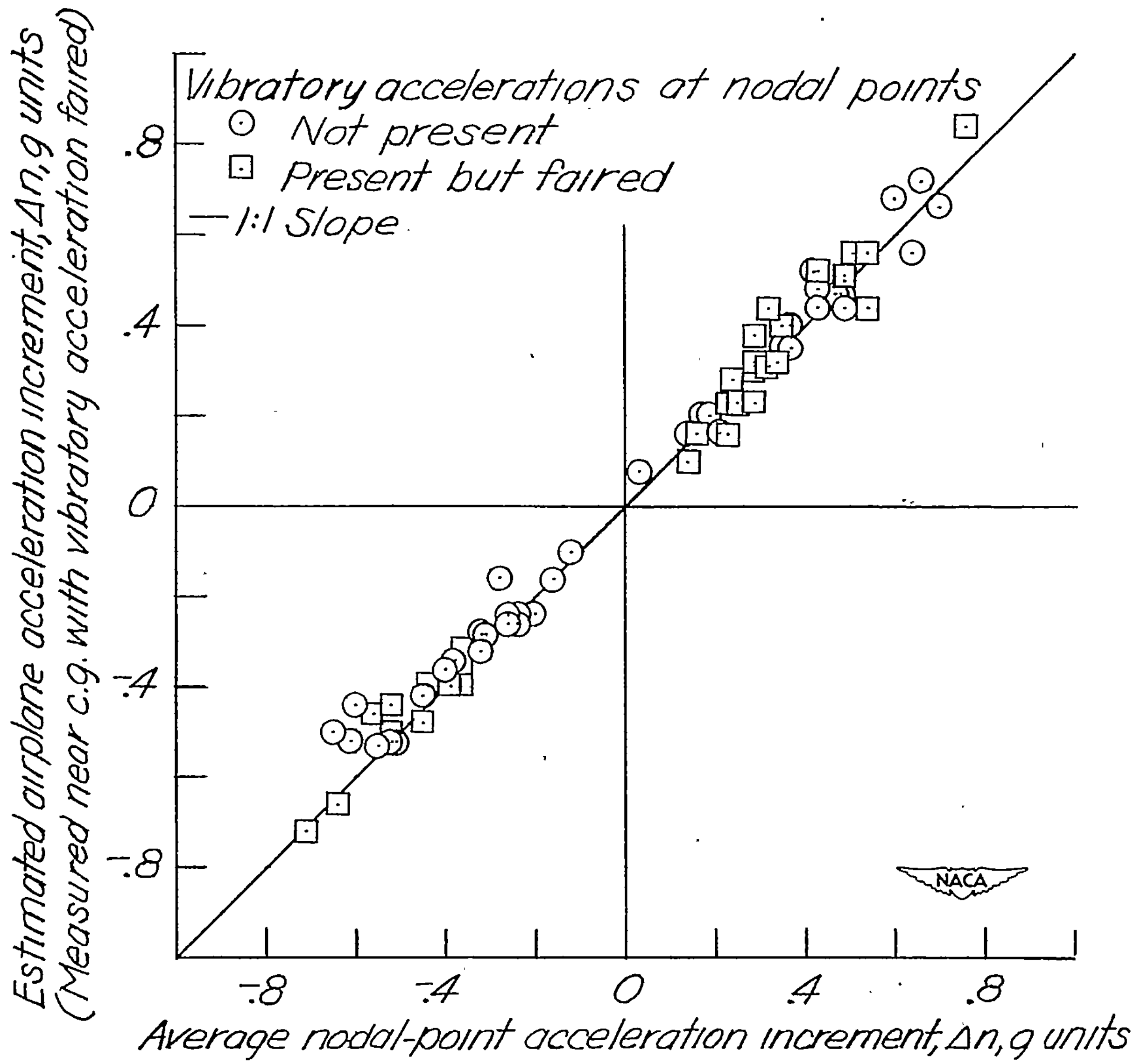


Figure 7.- Estimated airplane acceleration as a function of average nodal-point acceleration.

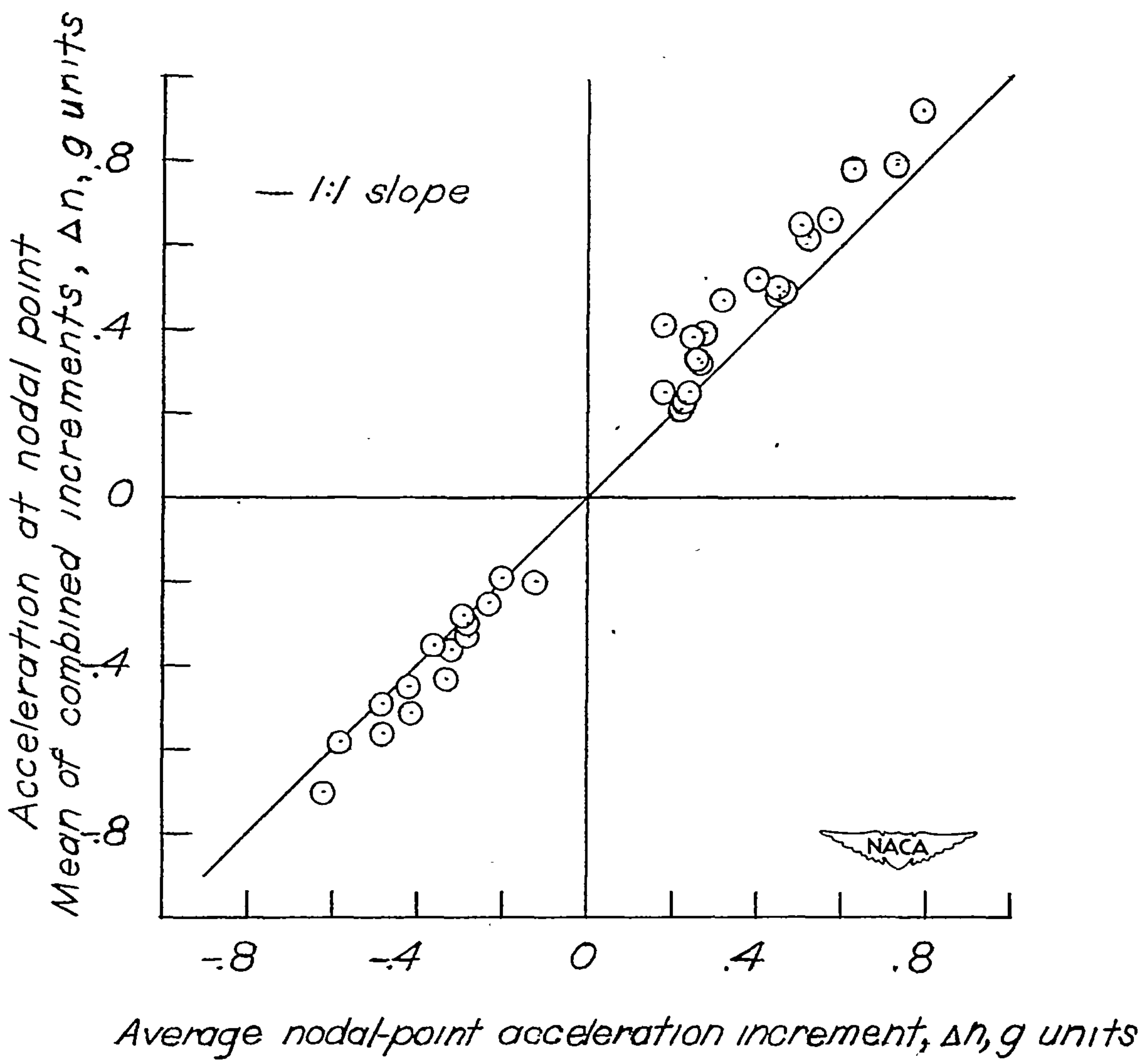


Figure 8.- Acceleration increment from mean of combined recorded outputs of nodal-point accelerometers as a function of average nodal-point acceleration increment.